# Long-term Global Radiation Measurements in Denmark and Sweden

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# Long-term Global Radiation Measurements in Denmark and Sweden

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**Abstract**. The climate, especially global radiation is one of the key factors influencing the energy yield of solar energy systems. In connection with planning and optimization of energy efficient buildings and solar energy systems it is important to know the climate data of the area where the buildings/systems are located. This study is based on yearly and monthly values of global radiation based on measurements from a climate station placed on the roof of building 119 at Technical University of Denmark in Kgs. Lyngby, from different Danish climate stations ran by Danish Meteorological Institute and from different Swedish climate stations of Swedish Meteorological and Hydrological Institute. The global horizontal radiation has been measured for a high number of years at all of these stations. The values show a tendency of increased annual global radiation, most likely due to decreased pollution of the atmosphere, increased duration of periods without clouds and/or combination of both these effects. Twenty years of measurements from a climate station in Lyngby, Denmark show that the global radiation increase is almost 3.5 kWh/m$^2$ per year, corresponding to a growth of 7 % for the last 20 years. The global radiation variation between the least sunny year to the sunniest year is 22%. Twenty-nine years of measuring of global radiation from twelve radiation stations across Sweden shows an increase of 3.1 kWh/m$^2$ per year. The increase is 87 kWh/m$^2$, corresponding to 9 % of global radiation growth during the last 29 years. The annual global radiation varies between 838 kWh/m$^2$/year in 1998 and 1004 kWh/m$^2$/year in 2002 with an average radiation of 932 kWh/m$^2$/year, corresponding to a radiation variation from the least sunny year to the sunniest year of 20 %.

## 1. Introduction

The climate data such as ambient air temperature, wind speed and especially solar radiation by means of direct (beam), diffuse and global are the key factors that determine the potential energy yield of any solar energy device, system or building. Therefore, the knowledge of the climate data of the area where the solar installations or buildings are planned to be located, in connection with orientation, tilt, possible shading and other local parameters, are essential input parameters for the prediction of solar energy system performance. Hence, these data are preconditions for reliable planning and optimization of energy efficient buildings and/or solar energy systems as well as for the estimates of the cost-effectiveness and for estimates of the rationality of the investment in a particular type of solar device at the particular location. This interaction takes place on several levels [1]:

- Solar collector:
  - The collector efficiency is influenced by beam radiation, diffuse radiation and ambient air temperature.

- Heat demand of the building:
  - Heat losses to the ambient are driven by the temperature difference between the house and the ambient (air and ground).
  - Solar radiation through the windows can be seen as heat gains in the period of the year when space heating is needed (heating season).
- Domestic hot water demand:

The cold water temperature from the mains varies over the year. This variation is mainly dependent on the average monthly ambient temperatures.

## 2. Global radiation measurements

The total amount of solar radiation received by a horizontal (ground) surface is called global radiation. Global radiation is thus the sum of the direct radiation from the sun and the diffuse radiation from the rest of the sky, ie solar radiation scattered by atmospheric molecules and particles or reflected by clouds. What is measured and read by the instruments is called *global irradiance*, more specifically *global horizontal irradiance* (GHI) or *global tilted irradiance* (GTI) which is the incident radiation power per unit area, and reported in units of W/m². By integrating over time it is the total radiation energy per unit area for a specified period, such as hours, days, months or years. This quantity is designated *global irradiation* and the monthly and annual values indicated are given in kWh/m² or MJ/m² (1 kWh/m² = 3.6 MJ/m²). Often, however, the term *Global radiation* as a general expression is used for both global irradiance (GHI and GTI) and global irradiation. However, in this case it should be clearly indicated whether it is instantaneous or average values of GHI or if it is accumulated values. This study is based on yearly and monthly values of GHI from:

- A climate station at Technical University of Denmark (DTU) in Kgs. Lyngby, Denmark, (Fig. 1),
- All Danish climate stations of Danish Meteorological Institute (DMI), (Fig. 2),
- Swedish radiation stations of Swedish Meteorological and Hydrological Institute (SMHI), (Fig. 3).

### *2.1. Climate station at Technical University of Denmark*

The climate station, described by [2, 3] shown on Fig. 1a, is placed on the roof of building 119 at Technical University of Denmark (DTU) in Kgs. Lyngby, Denmark. The latitude of the station is 55.79° N and the longtitude is 12.53° E. Weather data measurements have been carried out since 1989 and they are recorded every 2 minutes either integrated over 2 minutes or instantaneous. From these 2 minutes' data half hourly and hourly values are created. This study uses hourly values from 2 minute averages. GHI is measured with a Kipp & Zonen pyranometer CM11, shown on Figure 1b. The other measured data from the climate station are diffuse radiation on horizontal, beam radiation (W/m²), wind speed (m/s) and the ambient air temperature (°C). Due to maintenance, human factors and/or measuring device problems during the long term measurements there are some missing weather data, e.g. from a few minutes to whole days. These missing measured data were replaced with average data of previous and following minutes (days).

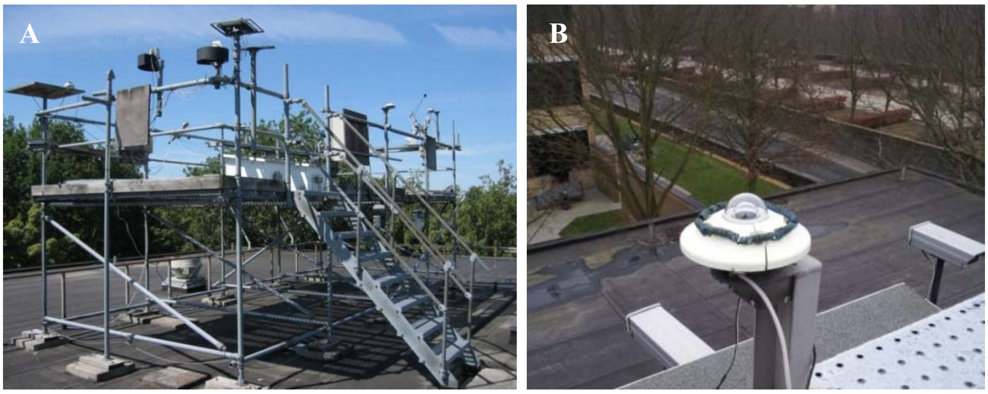


Figure 1. a) Climate station on the roof of building 119 at DTU, Lyngby, b) Pyranometer measuring the global horizontal irradiance on horizontal plane.

### 2.2. *Climate station at Technical University of Denmark*

Danish Meteorological Institute provides preliminary calculated values of average global radiation for the whole country from the last 20 years (1990 -2010) and the calculations are based on measurements from all climate stations in Denmark [4]. In Fig. 2 average yearly solar irradiations for the period 2001-2010 are shown for Denmark.

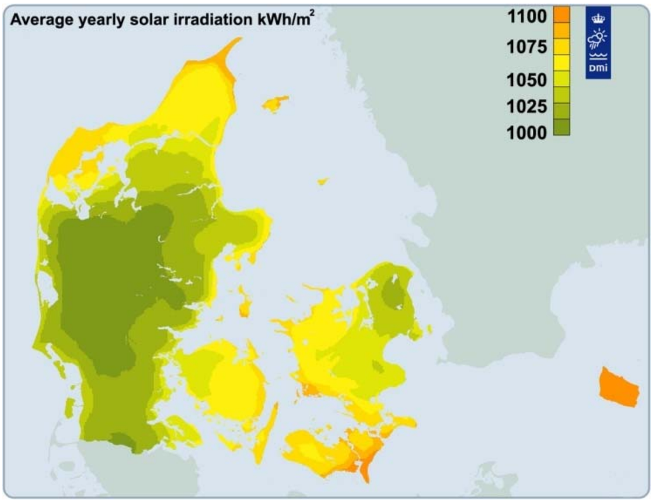


Figure 2. Average yearly solar irradiation on horizontal in Denmark obtained by DMI for period 2001-2010

### 2.3. *Radiation stations of Swedish Meteorological and Hydrological Institute*

The annual and seasonal GHI is presented as averages calculated over twelve radiation stations across Sweden. The stations included in the analysis are shown in Table 1. GHI have been measured with Kipp & Zonen CM10 or CM11 pyranometers and from 2008 CM21 pyranometers are used. The graphs of GHI shows yearly values with the unit kWh/m², see Figure 4 a,b,c. All of these stations have complete and nearly homogeneous data series from 1983. This means that errors have been corrected and missing measurement data have been replaced by interpolated or modelled data. Most important is that measurements at the radiation stations have been performed at the same sites during the whole period. Also the instrument upgrade from 2008 did not introduce any statistical significant change for annual data [5]. Minor systematic differences were found which mainly affected the winter values. These differences have not yet been corrected, but this has no significant influence on the results presented in this paper. The values may change slightly after a new treatment.

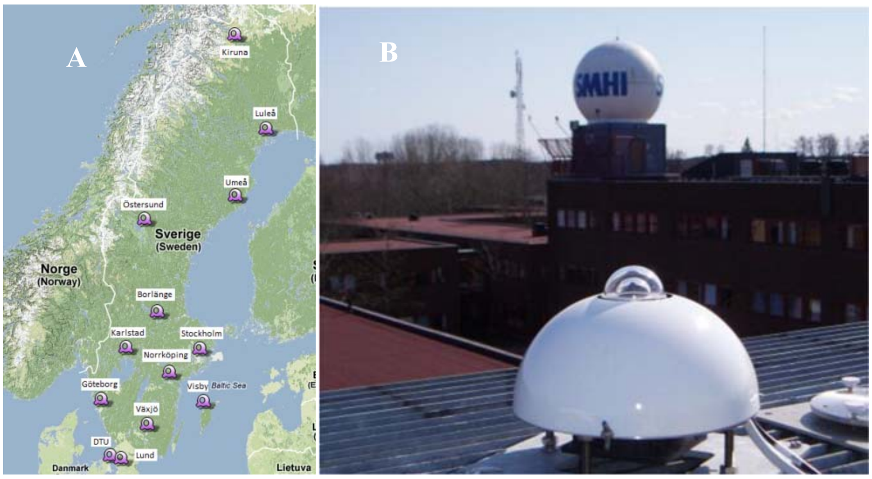


Figure 3. a) Map of twelve Swedish radiation stations of SHMI and the climate station at DTU in Denmark, b) SMHI radiation station instrument for GHI measurements [5]

Table 1. Location of the stations in the Swedish solar radiation station network operated by SMHI.

| Station | Latitude (° N) | Longtitude (° E) | Altitude (m) |
|---|---|---|---|
| **Kiruna** | 67.841 | 20.411 | 424 |
| **Norrköping** | 58.582 | 16.148 | 43 |
| **Visby** | 57.673 | 18.345 | 49 |
| **Luleå** | 65.544 | 22.111 | 32 |
| **Umeå** | 63.811 | 20.240 | 23 |
| **Östersund** | 63.197 | 14.480 | 374 |
| **Borlänge** | 60.488 | 15.429 | 164 |
| **Karlstad** | 59.359 | 13.472 | 46 |
| **Stockholm** | 59.353 | 18.063 | 30 |
| **Göteborg** | 57.688 | 11.980 | 94 |
| **Växjö** | 56.927 | 14.730 | 182 |
| **Lund** | 55.714 | 13.212 | 85 |

## 3. Weather data evaluation

### *3.1. Annual average of GHI from climate stations in Denmark and Sweden*

Twenty years of measuring GHI from the climate station at DTU is presented in table 2. An evaluation of these data shows an increase of GHI (Fig. 4a). An increase of about 3.5 kWh/m$^2$ per year is observed, corresponding to a yearly increase of 0.34 %. The increase is 68 kWh/m$^2$, corresponding to 7 % of GHI growth during the last 20 years. The increase of GHI is caused by decreased air pollution, a decrease in the number of clouds on the sky, or a combination of both effects. The annual GHI varies between 886 kWh/m$^2$/year in 1998 and 1088 kWh/m$^2$/year in 2009 with an average radiation of 1001 kWh/m$^2$/year, corresponding to a radiation variation from the least sunny year to the sunniest year of about 22 %. There is a large difference in incoming GHI for different areas in Sweden. As in Denmark, an increase of GHI is observed from average of twelve different Swedish radiation stations across the country during the last 29 years (Fig. 4c). Twenty-nine years of measuring GHI shows an increase of about 3.1 kWh/m$^2$ per year, corresponding to a yearly increase of 0.3 %. The increase is 87 kWh/m$^2$, corresponding to 9 % of GHI growth during the last 29 years. The annual GHI varies between 838 kWh/m$^2$/year in 1998 and 1004 kWh/m$^2$/year in 2002 with an average radiation of 932 kWh/m$^2$/year, corresponding to a radiation variation from the least sunny year to the sunniest year of 20 %.

Table 2. Measured solar global radiation at DTU, Denmark (kWh/m$^2$).

| Year | Monthly-Average | | | | | | | | | | | | Annual-Sum |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | |
| 1990 | 10 | 29 | 77 | 129 | 166 | 146 | 166 | 138 | 70 | 40 | 19 | 10 | 1000 |
| 1991 | 16 | 27 | 60 | 101 | 160 | 109 | 166 | 130 | 88 | 47 | 17 | 10 | 931 |
| 1992 | 15 | 24 | 60 | 90 | 185 | 206 | 185 | 111 | 85 | 41 | 16 | 10 | 1029 |
| 1993 | 16 | 25 | 73 | 127 | 170 | 173 | 119 | 121 | 53 | 41 | 11 | 8 | 936 |
| 1994 | 11 | 22 | 64 | 113 | 157 | 156 | 208 | 134 | 65 | 44 | 16 | 9 | 999 |
| 1995 | 14 | 24 | 51 | 112 | 155 | 157 | 185 | 163 | 68 | 45 | 19 | 12 | 1005 |
| 1996 | 10 | 26 | 63 | 128 | 114 | 151 | 157 | 146 | 95 | 44 | 13 | 10 | 957 |
| 1997 | 17 | 31 | 78 | 114 | 140 | 167 | 181 | 156 | 85 | 46 | 16 | 8 | 1040 |
| 1998 | 18 | 23 | 77 | 85 | 166 | 138 | 131 | 117 | 68 | 36 | 16 | 11 | 886 |
| 1999 | 12 | 29 | 53 | 111 | 150 | 161 | 173 | 129 | 99 | 47 | 18 | 11 | 994 |
| 2000 | 16 | 30 | 80 | 120 | 178 | 155 | 134 | 124 | 84 | 40 | 16 | 10 | 987 |
| 2001 | 11 | 36 | 70 | 94 | 170 | 168 | 176 | 123 | 69 | 37 | 15 | 9 | 980 |
| 2002 | 13 | 29 | 85 | 97 | 154 | 181 | 163 | 146 | 109 | 44 | 15 | 8 | 1043 |
| 2003 | 15 | 33 | 88 | 131 | 158 | 167 | 160 | 143 | 103 | 34 | 18 | 9 | 1059 |
| 2004 | 16 | 33 | 72 | 133 | 162 | 139 | 137 | 143 | 97 | 42 | 18 | 9 | 1001 |
| 2005 | 19 | 30 | 85 | 135 | 152 | 149 | 157 | 127 | 88 | 57 | 20 | 12 | 1031 |
| 2006 | 15 | 28 | 73 | 98 | 156 | 176 | 190 | 120 | 99 | 41 | 18 | 10 | 1025 |
| 2007 | 14 | 21 | 84 | 141 | 154 | 150 | 134 | 126 | 83 | 52 | 25 | 8 | 992 |
| 2008 | 11 | 30 | 72 | 122 | 193 | 182 | 179 | 114 | 84 | 47 | 19 | 8 | 1061 |
| 2009 | 12 | 30 | 63 | 156 | 171 | 190 | 161 | 143 | 92 | 48 | 12 | 10 | 1088 |
| 2010 | 16 | 25 | 70 | 120 | 117 | 160 | 174 | 120 | 85 | 56 | 18 | 14 | 974 |
| Average | 14 | 28 | 71 | 117 | 159 | 161 | 164 | 132 | 84 | 44 | 17 | 10 | 1001 |

The comparison of Danish and Swedish GHI measurements shows that the radiation stations in Sweden placed further North of DTU have lower global radiation values than the global radiation at DTU. At the global radiation station in Lund 1.8% higher average GHI has been measured, as compared with the average GHI measured at DTU, even though it is only at a latitude 0.08° southward of the DTU station. However, the radiation station in Visby placed 1.9° higher in latitude (to North) have a 7.7 % higher GHI. Figure 5 shows the annual values of GHI and sunshine hours for twelve SMHI climate stations which have been in operation since 1983. It appears that both solar radiation and sunshine hours has increased on average since the 1980s and also prove that there is a clear dependence on latitude in GHI and duration of sunshine hours in Sweden. Sunshine duration is the time that the ground surface is irradiated by direct solar radiation (i.e. sunlight reaching the earth's surface directly from the sun). In 2003, WMO defined sunshine duration as the period during which direct solar irradiance exceeds a threshold value of 120 W/m$^2$. This value is equivalent to the level of solar irradiance shortly after sunrise or shortly before sunset in cloud-free conditions. Swedish coastal and inland areas differ due to relative high number of clouds in the inland. Locations close to the coast are sunnier than locations in the inner part of the country, both in Sweden and in Denmark, see Fig. 2. The lowest mean yearly GHI was found in Kiruna with 784 kWh/m$^2$ while the highest mean yearly GHI during the period 1983-2010 is 1044 kWh/m$^2$ in Visby (located on the island of Gotland in the Baltic Sea), the difference is 25 %. The highest growth of GHI is found for Stockholm with +13 % and the lowest +5 % for Borlänge. The average linear trend in GHI during the period 1983-2011 for all SMHI stations is +9 %, for the period 1990-2010 at DTU it is +7 % and +8 % for Denmark in general.

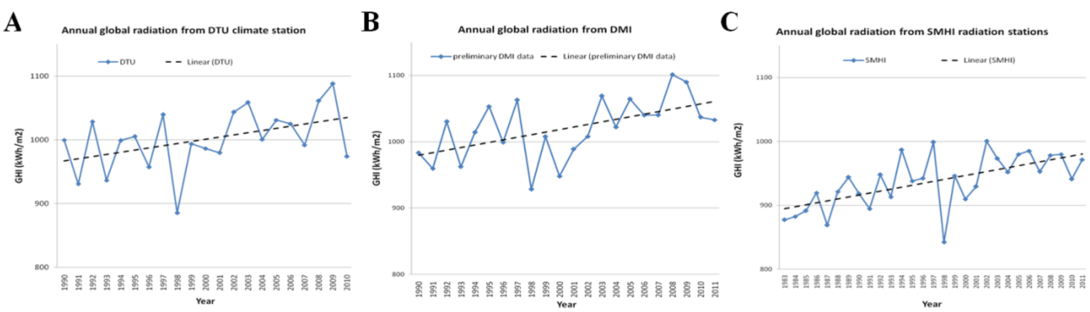


Figure 4. Annual GHI from a) climate station at DTU in Denmark, b) preliminary DMI results measured and calculated data for Denmark, c) twelve SMHI stations in Sweden.

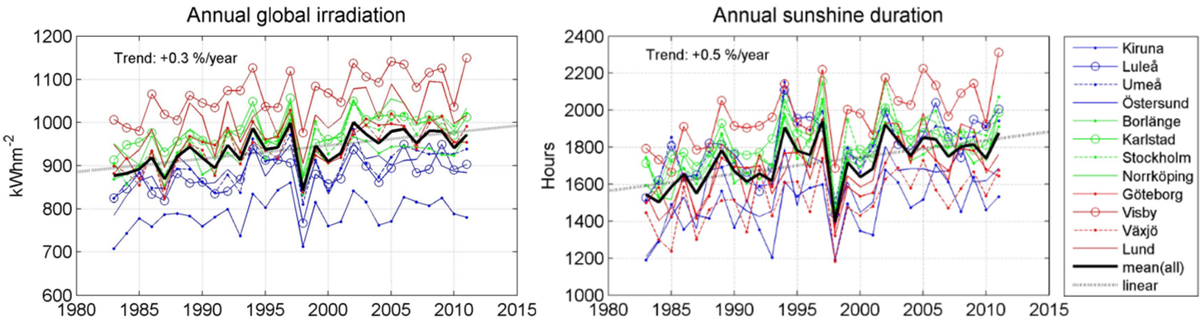


Figure 5. Annual values of GHI and sunshine hours since 1983 to 2011 for twelve SMHI stations.

### 3.2. *Monthly average GHI from climate stations in Denmark and Sweden*

The variations of the monthly average GHIs on horizontal (Fig. 6 and 7a,b) are higher in the summer period than in the winter period, where the variations are not significant, both for Swedish and Danish measurements.

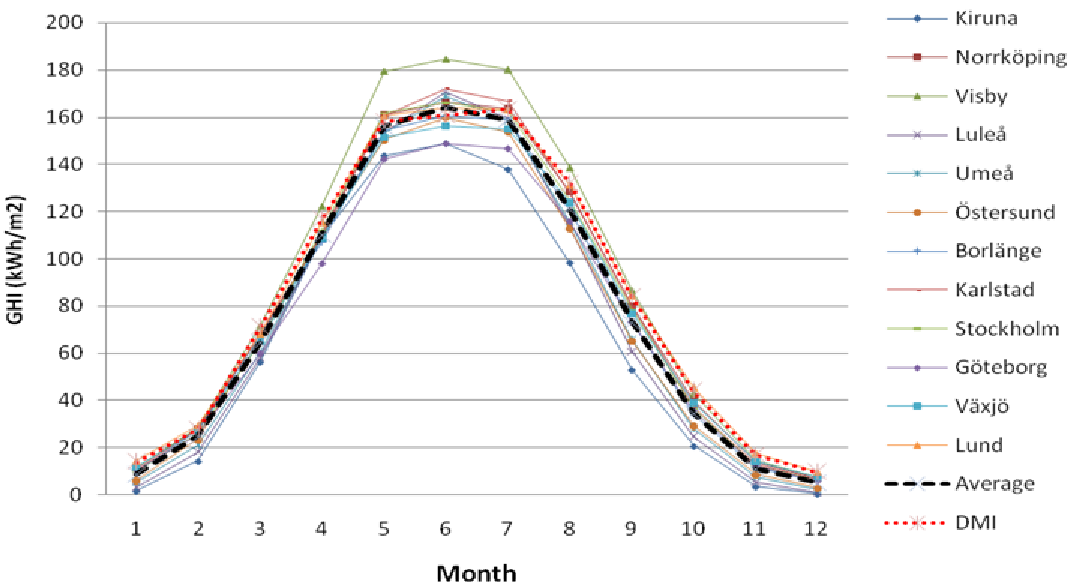


Figure 6. Monthly average GHI from at SMHI radiation stations in comparison with DTU climate station.

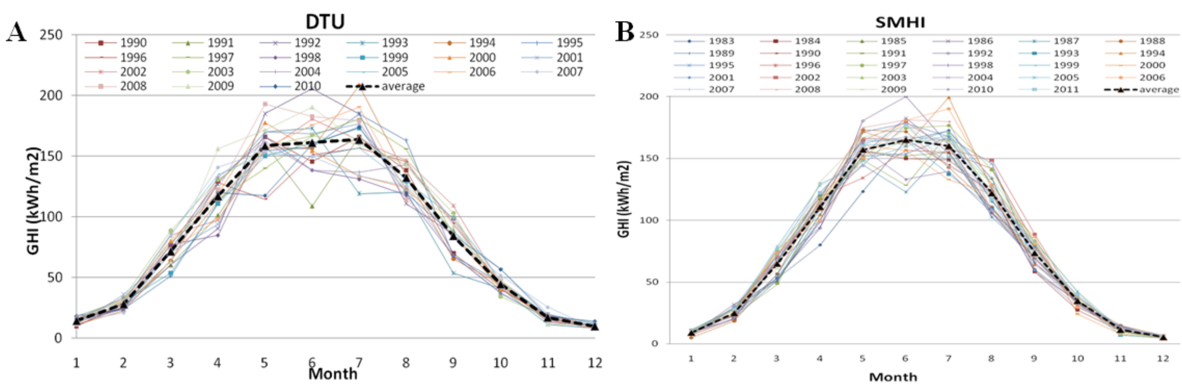


Figure 7. Monthly GHI from a) Climate station at DTU in Denmark, b) SMHI radiation stations.

### *3.3. Seasonal average GHI from climate stations in Denmark and Sweden*
Figure 8 shows the seasonal average of global radiation on horizontal. The summer period is from June to August, autumn months are September to November, winter is from December to February and spring months are March, April and May. The highest increase of GHI is recorded for the spring months. Autumn and winter months are without significant growth of GHI. The variation from year to year is large and heavily influenced by conditions during the summer.

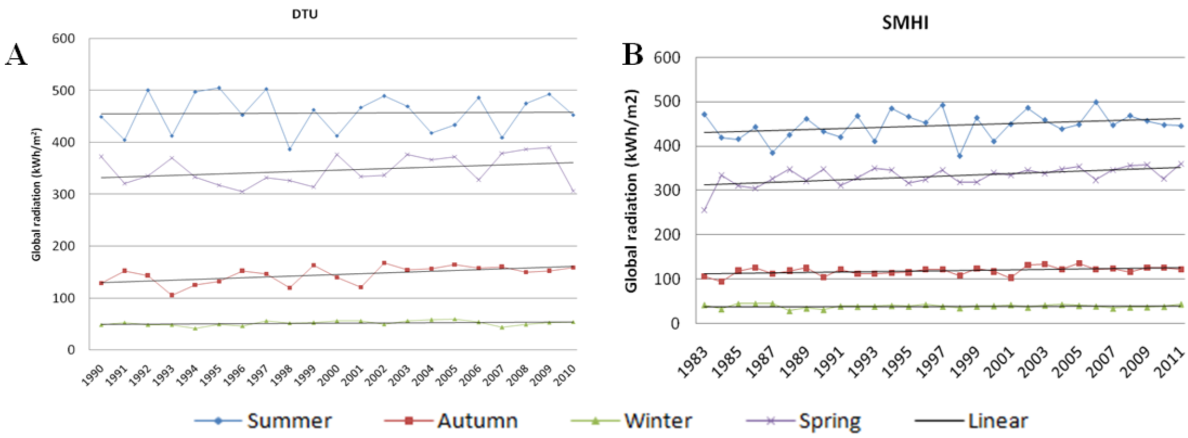


Figure 8. Seasonal average of GHI from a) Climate station at DTU, b) SMHI radiation stations.

## 4. Conclusions
Sweden is a long country from North to South. There is generally less solar radiation on horizontal in the North compared to the South because the sun is usually lower on the sky in the North. But there are also other effects that disturb it. The sunshine hours vary a lot between coastal and inland areas due to differences in the clouds. As the days are short and the sun is low in winter in Sweden, the annual value are severely affected by conditions during the summer. The two main factors that affect global radiation are the sun altitude and cloudiness. The large periodic variation over the year gives the variation in cloudiness in the annual and monthly values from year to year. For example, the cloudy summer of 1998 is significant in the charts, both for Danish and Swedish GHI measurements. According to [5] the location of a station in relation to its distance from sea or big lakes is of great importance for the cloud conditions and therefore the total income of GHI to the surface, (Fig. 2). A good example is when comparing the stations in Växjö (an inland site in Southern Sweden) and Visby (surrounding by Baltic sea), they are separated by only 0.72° in latitude (Fig. 1) and even though Visby is the northernmost of these two stations the GHI is 12 % higher. This might be useful for planning and deciding of future placement (location) of large solar plants and/or solar energy systems in connection with gathering more solar energy from higher solar radiation. Since the mid-1980s until now, the annual GHI has increased by over 9 % in Sweden. Similar tendencies have been observed all across Europe [7]. There were also measurements before the 1980s, and these data suggest that the global radiation was higher in the 1960s than during the 1980s. The decline from the 1960s to the 1980s and the subsequent increase in the beginning of the 2000s is often referred to in the international climate research as global dimming and brightening. Unfortunately, the older measurements are not homogeneous with current measurements and it is therefore currently not possible to compare the levels observed so far in the 2000s with those observed for example in the 1960s. Hopefully, the older data will eventually be added to the current test series, but before that, extensive work have to be done by estimating the quality of the older data and to develop the necessary corrections. From previous findings [6,7] the ambient air temperature, mostly due to increased greenhouse gas emissions, shows a small increase as well. But generally the ambient air temperature does not have a high influence on the thermal performance of solar collectors compared to the influence of the global solar radiation.

## 5. Conclusions

From weather data measurements it is obvious that there is a trend of increased yearly GHI in Denmark and Sweden. In the time series of GHI, there exist clear increasing trends at all stations during the whole period under consideration, most likely due to decreased pollution of the atmosphere, increased duration of periods without clouds, or a combination of both. SMHI measurements in Sweden shows a clear dependence on latitude and position of the station, according to sea and/or big lakes, in GHI. The average linear trend in GHI during the period 1983-2011 for Sweden in general is +9 %, for the period 1990-2010 at DTU it is +7 % and +8 % for Denmark in general.

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